



Article

Geochemistry and Petrogenesis of Mesoproterozoic Dykes of the Irkutsk Promontory, Southern Part of the Siberian Craton

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Abstract: We present new geochemical and Nd isotopic data on two Mesoproterozoic Listvyanka (1350 ± 6 Ma) and Goloustnaya (1338 ± 3 Ma) mafic dyke swarms located in the Irkutsk Promontory of the southern part of the Siberian craton. Listvyanka dykes are sub-vertical with NNE trend, while Goloustnaya dykes are characterized by prevailing W trend. Listvyanka and Goloustnaya dykes are composed of medium to coarse grained dolerites. All dolerites correspond to sub-alkaline tholeiitic basalts according to their major-element compositions with lower to moderate mg#, varying from 36 to 54. The trace and rare earth element abundances in Listvyanka and Goloustnaya dolerites are generally close to basalts of the oceanic island basalts (OIB) type. The Listvyanka dolerites demonstrate slightly positive $\epsilon\text{Nd}(t)$ values varying from +1.1 to +1.5, while the Goloustnaya dolerites are characterized by lower $\epsilon\text{Nd}(t)$ values ranging from −0.9 to +0.1. Geochemical and isotopic affinities of the Listvyanka dolerites suggest their enrichment by a mantle plume related source. For the Goloustnaya dolerites, we assume also some additional lithospheric input to their mantle plume-related source. The emplacement of both studied dolerites took place in intracontinental extensional setting, caused by a single rising mantle plume. Listvyanka and Goloustnaya dolerites are coeval to several mafic magmatic events in northern Laurentia and likely represent part of the Mesoproterozoic plumbing system of a Siberian–Laurentian Large Igneous Province.

Keywords: dolerites; dykes; geochemistry; Nd isotopes; Mesoproterozoic; Siberian craton

1. Introduction

The time period of 1.70–0.75 Ga is often described as the Super Gap [1,2], Boring Billion [3] or Earth's Middle Age [4]. Cawood and Hawkesworth [4] showed that during this period there were no global glaciations, no orogenic gold, no volcanic-hosted massive sulfide deposits, no major iron formations and just a few preserved passive margin sequences. At the same time, anorthosite complexes and Large Igneous Provinces (LIPs) were abundant in this time period. The close proximity of southern Siberia and northern Laurentia (cratonic part of North America) during this time is postulated in recent paleogeographic reconstructions, e.g., [5–7]. Alternative Siberia vs. Laurentia

reconstruction with northern Siberia attached to western Laurentia [8–10], or with northern Siberia attached to northern Laurentia [11,12] have been analyzed and found to: (i) contradict Mesoproterozoic paleomagnetic data from both continents, e.g., [13–17]; (ii) be mostly inconsistent with LIPs records in both continents, e.g., [7,18]; (iii) contain more geological mismatches than matches, e.g., [13]. Additionally, the connection between northern Siberia and western Laurentia is inconsistent with many geological and paleomagnetic lines of evidence of the connection between Australia–Antarctica with western Laurentia in Mesoproterozoic, e.g., [16,19–23]. It is also suggested that Siberia and Laurentia were parts of the Mesoproterozoic supercontinent Columbia (aka Nuna), formed between 1.8 and 1.6 Ga and partially disintegrated between 1.4 and 1.2 Ga, e.g., [19,24], and of the Neoproterozoic supercontinent Rodinia, formed between 1.1 and 0.9 Ga and broken apart after 0.8 Ga, e.g., [14]. However, although Mesoproterozoic LIP-related magmatic rocks are widely spread in northern Laurentia, e.g., [4,7], their occurrences are limited in the southern part of the Siberian craton. Gladkochub et al. [2,18] suggested the almost complete absence of Mesoproterozoic magmatism in the southern part of the Siberian craton, but this conclusion was based mainly on the absence of reliable age determinations at that time.

In 2016, Ernst et al. [7] reported the ages of two Mesoproterozoic intrusions in the southern part of the Siberian craton: 1350 ± 6 Ma Listvyanka dyke and 1258 ± 5 Ma Srednecheremshanskaya dyke. The former is nearly coeval to the 1353 ± 2 Ma Barking Dog gabbro sill in northern Laurentia and may represent the same large igneous event. The latter is slightly younger than the huge 1267–1270 Ma Laurentian Mackenzie LIP. These findings potentially provide Mesoproterozoic piercing points between southern Siberia and northern Laurentia. Recently Gladkochub et al. [25] reported the 1338 ± 3 Ma age for another dyke swarm (Goloustnaya) in the southern part of the Siberian craton, but the nature of these dykes is still unclear.

Here we present the geochemical and isotopic characteristics of Listvyanka and Goloustnaya swarms and discuss their origin and geodynamic interpretations.

2. Geological Setting

The Siberian craton was assembled in Paleoproterozoic by amalgamation of Archean and Paleoproterozoic terranes (building blocks), e.g., [26–28]. Building blocks of the craton are welded by ~1.8–2.0 Ga orogenic belts and suture zones [26–29]. The southern part of the craton (Irkutsk Promontory) is subdivided into Archean Tungus and Magan terranes and Paleoproterozoic Akitkan fold belt (Figure 1). In Irkutsk Promontory, the basement rocks of Tungus terrane and Akitkan fold belt are exposed in the Sharyzhalgai and Baikal inliers, respectively. The basement rocks of Magan terrane are completely covered by Phanerozoic sedimentary rocks.

Mesoproterozoic dykes in the Irkutsk Promontory are exposed along the coast of Lake Baikal near the village of Listvyanka (Sharyzhalgai inlier) and in the Goloustnaya area (Baikal inlier) (Figure 1).

The Listvyanka dykes include one relatively thick dyke (30 m) and several smaller dykes (Figure 3). They intrude Archean and Paleoproterozoic metamorphic and igneous rocks of the Sharyzhalgai inlier. The dykes are sub-vertical with a NNE trend (10 – 20°).

The Listvyanka dykes are composed of medium- to coarse-grained dolerite. They consist of rock-forming plagioclase and clinopyroxene, minor amphibole, biotite, quartz and ore minerals, as well as accessory apatite, titanate, zircon and baddeleyite (Figure 2a). The rocks were altered by oxidation, saussuritization, albitization and sometimes carbonatization. Pyroxene and biotite are partly replaced by amphibole and chlorite, respectively. The U–Pb baddeleyite and zircon age of the thick dyke is 1350 ± 6 Ma [7].

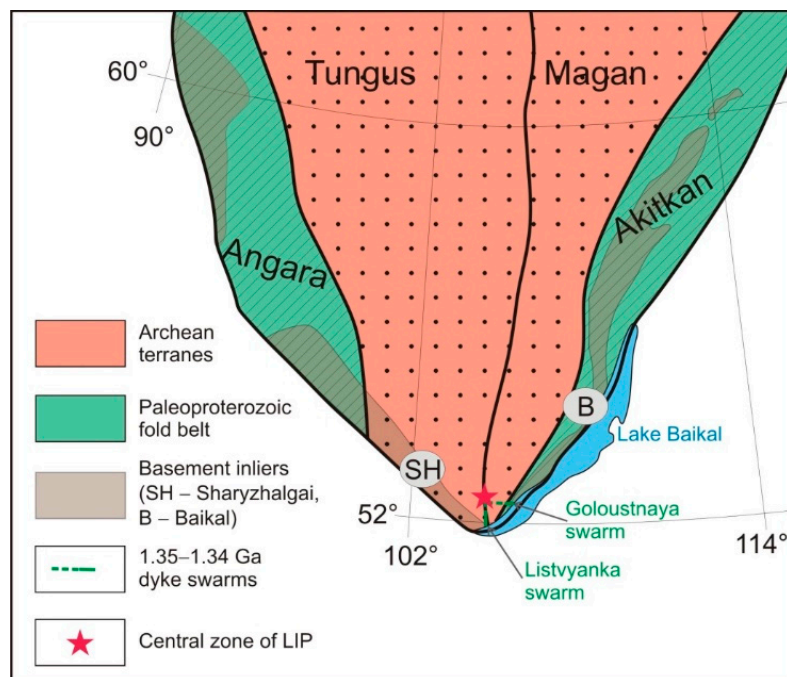


Figure 1. Major tectonic elements of the Irkutsk Promontory of the southern part of the Siberian craton (modified after [26–28]).

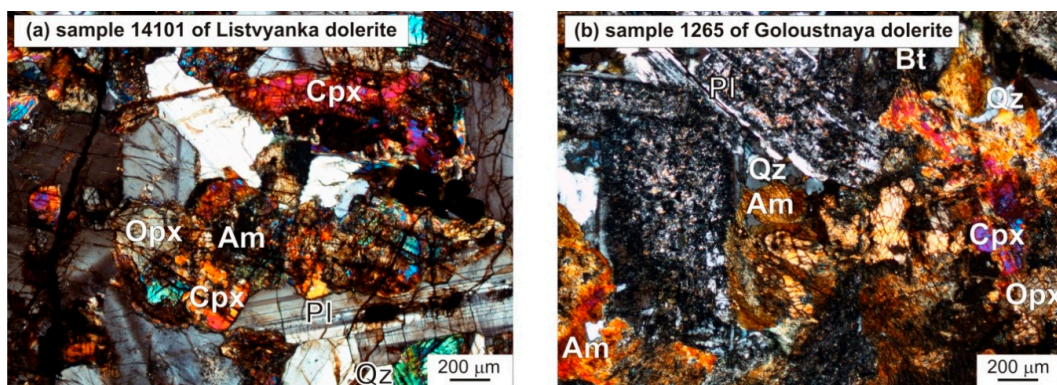


Figure 2. Photomicrographs of Listvyanka and Goloustnaya dolerites: (a) sample 14101 of Listvyanka dolerite and (b) sample 1265 of Goloustnaya dolerite. Mineral abbreviations: Amp, amphibole; Cpx, clinopyroxene; Opx, orthopyroxene; Pl, plagioclase; Bt, biotite; Qz, quartz.

A series of dykes and dyke-like intrusions were found along the south-eastern shore of Lake Baikal north of the Bolshaya Goloustnaya village (the Goloustnaya area). These dykes cut mainly Paleoproterozoic migmatites, granite gneisses, and granites of the Goloustnaya block of the Baikal inlier (Figure 4). The contact of these dykes with host-rocks is sharp and clear, but sometimes they have a curved configuration. The dykes are sub-vertical with a prevailing W trend. Thicknesses of these dykes vary from two meters to one hundred meters. Dykes are composed of medium and coarse-grained dolerite. Rock-forming minerals are clinopyroxene and plagioclase (Figure 2b). Less abundant are orthopyroxenes, amphibole, biotite, quartz, ore minerals and sometimes K-feldspar. Apatite, titanite, rutile, zircon and baddeleyite are typical accessory minerals. Some dolerites underwent low-temperature alteration, which caused partial saussuritization of plagioclase, clinopyroxene replacement by amphibole, and biotite replacement by chlorite, as well as formation of secondary epidote, quartz, hydrous ferric oxides, albite and calcite. The U–Pb baddeleyite and zircon age of dolerite is 1338.5 ± 6.9 Ma and the weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ zircon age is 1338.0 ± 2.9 Ma [25].

Table 1. Geochemical compositions of the Listvyanka and Goloustnaya dolerites.

Location		Listvyanka						Goloustnaya				
Dyke Number		1		2		3		4				
Sample	1283	1283a	14101	14102	14103	1261	1401	1263	1264	1265	1402	1403
SiO ₂ , wt. %	48.57	48.23	49.28	47.71	47.52	48.60	47.30	49.46	48.88	50.36	47.37	46.72
TiO ₂	2.24	2.58	1.64	2.29	2.34	2.75	2.75	2.32	2.08	2.00	2.67	2.75
Al ₂ O ₃	13.55	12.60	14.75	13.20	13.75	12.84	13.05	12.72	14.46	14.28	13.40	13.50
Fe ₂ O ₃	3.31	3.21	3.13	3.45	3.66	3.42	4.08	1.76	2.94	2.31	3.61	3.50
FeO	10.19	11.37	8.53	10.89	11.12	10.78	10.68	11.82	9.92	9.56	11.03	10.76
MnO	0.21	0.23	0.17	0.22	0.24	0.19	0.20	0.22	0.18	0.18	0.20	0.19
MgO	5.91	6.71	6.24	6.67	6.25	5.99	5.94	6.13	5.54	5.35	6.18	6.53
CaO	9.48	9.72	10.48	9.35	8.52	8.93	9.53	7.79	8.72	8.63	9.27	9.53
Na ₂ O	2.71	2.50	2.48	2.73	2.26	2.18	1.86	2.72	2.40	2.52	2.74	2.31
K ₂ O	0.5	0.31	0.39	0.66	1.26	0.87	1.15	0.82	0.83	0.78	0.62	0.66
P ₂ O ₅	0.28	0.28	0.19	0.31	0.26	0.37	0.38	0.44	0.36	0.46	0.27	0.31
LOI	2.19	2.29	1.68	2.03	2.83	2.91	3.10	3.33	3.04	3.04	2.86	3.28
H ₂ O [−]	0.14	0.09	0.19	0.12	0.13	0.24	0.14	0.28	0.31	0.22	0.11	0.11
CO ₂	0.69	0.23	0.54	0.24	0.11	<0.06	-	0.09	0.09	0.09	-	0.28
Total	99.97	100.35	99.69	99.87	100.25	100.06	100.16	99.90	99.74	99.78	100.33	100.43
Rb, ppm	15	7	8	22	32	26	64	26	20	20	25	21
Sr	361	335	324	350	270	227	242	225	255	267	230	194
Y	25	24	16	24	20	34	36	38	34	39	28	30
Zr	170	149	97	150	124	212	218	247	221	254	159	184
Nb	25	25	24	24	21	24	25	30	24	28	17	20
Ba	150	74	113	154	333	283	293	315	335	390	242	233
La	21.13	19.96	13.92	21.65	18.04	24.81	29.96	30.69	24.31	29.54	19.29	22.70
Ce	45.56	43.06	29.79	48.03	38.16	55.46	65.76	67.65	55.33	67.01	43.44	50.67
Pr	6.10	5.93	3.86	6.13	4.90	7.25	8.11	8.63	7.23	8.63	5.46	6.27
Nd	24.86	24.26	16.07	26.39	21.33	29.37	33.41	36.07	30.52	36.62	23.12	25.98
Sm	5.62	5.62	3.91	5.93	4.79	7.15	8.22	8.51	6.92	8.47	5.36	6.57
Eu	1.90	1.78	1.26	1.80	1.52	2.03	2.32	2.31	2.10	2.49	1.74	2.05
Gd	5.02	4.93	3.27	4.90	4.00	5.77	7.06	6.76	5.68	7.05	5.12	5.78
Tb	0.76	0.75	0.50	0.74	0.59	0.95	1.11	1.10	0.95	1.16	0.83	0.91
Dy	4.69	4.53	2.97	4.56	3.61	5.96	6.46	6.73	5.95	6.98	5.08	5.32
Ho	0.90	0.88	0.59	0.92	0.74	1.24	1.28	1.40	1.22	1.40	1.00	1.08
Er	2.42	2.22	1.66	2.48	1.98	3.09	3.21	3.48	3.16	3.58	2.65	2.81

Table 1. Cont.

Tm	0.37	0.32	0.22	0.35	0.28	0.45	0.48	0.51	0.48	0.53	0.39	0.42
Yb	2.26	2.04	1.34	2.11	1.74	2.75	2.90	3.14	2.84	3.25	2.31	2.38
Lu	0.33	0.31	0.22	0.32	0.29	0.42	0.45	0.50	0.45	0.50	0.34	0.36
Hf	4.08	3.61	2.66	3.90	3.30	5.04	5.33	5.97	5.29	6.10	4.08	4.65
Ta	1.65	1.42	2.47	1.53	1.35	1.44	1.53	1.78	1.42	1.72	0.78	1.28
Th	1.90	1.54	1.34	2.03	1.71	1.78	2.60	2.53	1.95	2.45	1.61	1.82
U	0.50	0.34	0.33	0.41	0.34	0.94	0.97	0.63	0.69	0.72	0.41	0.43
mg#	48	50	54	50	48	48	46	49	48	49	48	50
(La/Yb) _n	6.06	6.32	6.70	6.65	6.70	5.84	6.68	6.31	5.54	5.89	5.40	6.16
Eu/Eu*	1.10	1.05	1.08	1.03	1.07	0.97	0.94	0.94	1.03	0.99	1.03	1.02
Nb/Nb*	1.36	1.51	1.89	1.25	1.26	1.22	0.95	1.17	1.19	1.13	0.77	0.95
Ti/Ti*	0.99	1.15	1.08	1.00	1.26	1.01	0.85	0.72	0.78	0.61	1.20	1.05
Location												
Goloustnaya												
Dyke Number	4	5	6	7	8	9						
Sample	1404	1266	1267	1412	1414	1278	1279	1425	1428	1435	1437	1438
SiO ₂ , wt. %	49.31	49.02	46.96	47.66	50.21	49.25	49.42	48.48	47.69	48.33	48.77	47.94
TiO ₂	2.95	2.57	3.18	2.77	2.43	2.91	2.95	2.62	2.88	2.58	2.33	3.31
Al ₂ O ₃	13.65	15.37	11.85	13.60	15.80	13.70	13.30	14.30	13.78	14.32	13.04	13.57
Fe ₂ O ₃	3.80	2.90	4.20	4.02	3.43	4.28	4.40	4.25	4.05	4.34	4.62	4.61
FeO	10.64	9.28	11.52	10.72	8.82	10.72	10.68	9.53	10.04	9.85	8.84	11.23
MnO	0.18	0.17	0.16	0.18	0.15	0.19	0.19	0.18	0.19	0.18	0.16	0.20
MgO	4.18	4.24	5.53	5.60	3.91	3.95	3.95	5.16	6.18	5.24	6.08	4.09
CaO	8.14	8.29	7.43	9.00	8.27	8.21	8.13	9.63	9.75	8.80	8.84	7.96
Na ₂ O	3.02	2.63	1.65	2.43	3.08	2.41	2.72	2.53	2.19	2.33	2.21	2.37
K ₂ O	0.81	0.79	0.56	0.90	0.72	1.19	1.2	0.69	0.6	0.81	1.48	1.07
P ₂ O ₅	0.74	0.42	0.41	0.34	0.44	0.65	0.57	0.33	0.26	0.32	0.24	0.66
LOI	2.84	3.37	4.02	2.72	3.00	2.74	2.48	2.06	2.21	2.26	2.69	2.67
H ₂ O [−]	0.12	0.30	0.29	0.19	0.14	0.16	0.13	0.13	0.20	0.08	0.17	0.06
CO ₂	-	0.56	1.94	0.24	<0.06	<0.06	0.17	0.41	0.15	0.36	0.31	0.22
Total	100.38	99.91	99.70	100.37	100.40	100.36	100.29	100.30	100.17	99.80	99.78	99.96
Rb, ppm	26	30	23	24	26	31	30	22	19	26	65	28
Sr	290	269	144	236	391	242	262	276	254	259	254	256
Y	45	34	35	33	41	45	43	32	27	31	24	42
Zr	302	234	233	222	294	305	291	208	166	190	146	268
Nb	33	25	29	26	29	33	33	22	17	20	15	32
Ba	459	341	166	384	356	488	450	298	259	436	426	463

Table 1. Cont.

La	37.81	27.10	25.46	26.62	35.16	35.97	33.55	24.27	19.99	22.22	17.30	34.43
Ce	85.88	61.49	58.28	61.05	79.08	82.94	77.53	56.00	45.91	50.66	39.10	78.99
Pr	10.60	7.92	7.69	7.48	9.62	10.68	9.97	6.78	5.71	6.29	4.96	9.81
Nd	43.75	32.92	31.72	30.24	39.07	44.48	42.18	28.16	23.83	26.80	20.68	40.90
Sm	10.36	7.51	7.92	7.50	9.38	10.30	9.40	6.86	6.15	6.59	5.14	10.13
Eu	3.16	2.24	2.13	2.33	2.82	2.91	2.78	2.09	1.87	2.06	1.59	2.95
Gd	9.01	6.61	6.38	6.36	8.03	8.32	7.91	6.10	5.10	5.84	4.68	8.75
Tb	1.33	1.04	1.05	1.02	1.31	1.32	1.28	0.99	0.85	0.96	0.75	1.35
Dy	8.18	6.20	6.30	6.08	7.61	8.03	7.59	5.78	5.00	5.66	4.52	7.89
Ho	1.63	1.27	1.26	1.22	1.53	1.66	1.57	1.17	1.02	1.06	0.89	1.58
Er	4.17	3.13	3.30	3.20	3.85	4.18	3.94	3.04	2.52	2.87	2.47	4.00
Tm	0.61	0.45	0.49	0.48	0.56	0.60	0.57	0.42	0.38	0.43	0.35	0.57
Yb	3.74	2.83	3.06	2.85	3.43	3.64	3.44	2.71	2.27	2.63	2.10	3.46
Lu	0.53	0.44	0.48	0.44	0.54	0.55	0.54	0.40	0.35	0.39	0.31	0.51
Hf	7.62	5.46	5.58	5.48	7.13	7.36	6.81	5.27	4.11	4.95	3.55	6.74
Ta	2.12	1.55	1.73	1.60	1.84	2.04	2.01	1.44	0.78	1.29	1.00	2.12
Th	3.42	2.28	2.08	2.40	3.24	3.03	2.89	2.16	1.60	1.84	1.46	2.88
U	0.80	0.83	0.98	0.57	0.80	0.74	0.67	0.51	0.41	0.51	0.49	0.96
mg#	38	43	43	45	41	36	36	45	49	44	50	36
(La/Yb) _n	6.54	6.20	5.38	6.05	6.64	6.40	6.32	5.79	5.69	5.47	5.33	6.43
Eu/Eu*	1.01	0.98	0.92	1.04	1.00	0.97	0.99	1.00	1.03	1.02	1.00	0.97
Nb/Nb*	1.17	1.10	1.36	0.87	0.91	1.07	1.15	1.02	0.81	1.01	0.68	1.07
Ti/Ti*	0.72	0.86	1.05	0.94	0.66	0.74	0.80	0.95	1.21	0.98	1.12	0.83

mg# = $Mg \times 100 / (Mg + Fe^{2+})$, where $Mg = MgO/40.31$, $Fe^{2+} = (Fe_2O_3^* \times 0.8998 \times 0.85)/71.85$; $Eu/Eu^* = Eu_n / (\sqrt{(Sm_n \times Gd_n)})$; $Nb/Nb^* = Nb_{pm} / (\sqrt{(Th_{pm} \times La_{pm})})$; $Ti/Ti^* = Ti_{pm} / (\sqrt{(Sm_{pm} \times Gd_{pm})})$; n, chondrite-normalized elements; pm, primitive mantle-normalized elements.

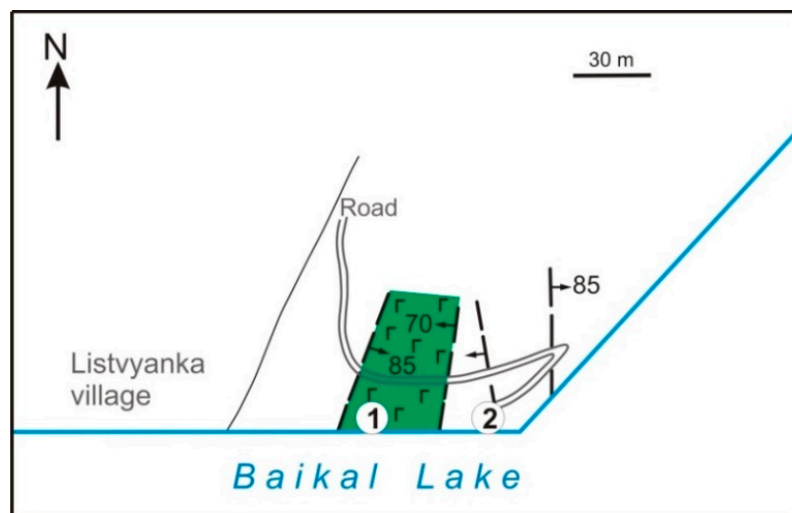


Figure 3. Sketch map showing the location of several dykes of the Listvyanka swarm along the western short of Lake Baikal (modified after [7]). The numbers of dykes according to Table 1 are shown in circles.

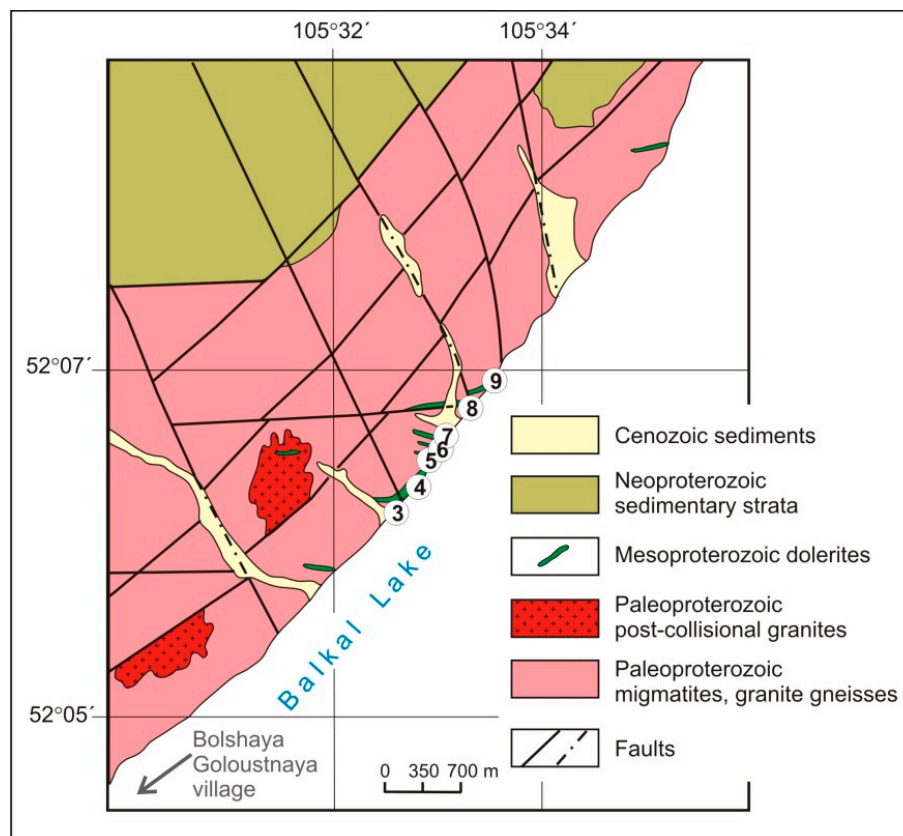


Figure 4. Geological scheme of the Goloustnaya area, showing the locations of dykes of Goloustnaya swarm (modified after [25]). The numbers of dykes according to Table 1 are shown in circles.

3. Methods

Five samples from two Listvyanka dykes and 19 samples from five Goloustnaya dykes were collected for analysis of major-oxide, trace-element, REE abundances, and Nd isotope systematics. Analytical data are summarized in Tables 1 and 2.

Table 2. Sm–Nd isotopic data for the Listvyanka and Goloustnaya dolerites.

Sample	T, Ma	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\epsilon_{\text{Nd}}(\text{t})$	$T_{\text{Nd}}(\text{DM})$
				$\pm 2\sigma$			Ma
Listvyanka dolerites							
1283	1350	4.50	18.35	0.1325	0.512146 ± 10	1.5	1882
14101	1350	2.97	11.65	0.1374	0.512175 ± 10	1.2	1947
14103	1350	4.06	16.46	0.1330	0.512129 ± 11	1.1	1926
Goloustnaya dolerites							
1265	1338	5.23	21.10	0.1339	0.512060 ± 11	−0.5	2079
1267	1338	6.22	24.98	0.1345	0.512078 ± 11	−0.2	2059
1279	1338	6.32	25.91	0.1316	0.512021 ± 10	−0.9	2094
1401	1338	4.00	15.33	0.1407	0.512152 ± 10	0.1	2080
1428	1338	3.33	12.46	0.1444	0.512140 ± 10	−0.7	2217

Major elements were analysed by wet chemistry at the Centre for Geodynamics and Geochronology of the Institute of the Earth's Crust SB RAS (Irkutsk, Russia). Trace elements and rare earths were determined by inductively coupled plasma mass spectrometry (ICP-MS) on an Agilent Technologies Agilent 7500ce analyzer at the Limnological Institute SB RAS (Irkutsk, Russia). For ICP-MS, the samples were fused with LiBO_2 following the procedure of Panteeva et al. [30]. Calibrations were with internal and international standards G-2, GSP-2, JG-2, and RGM-1. Analytical accuracy was 0.5–1.0% for major oxides and up to 5% for trace elements and REE.

Sm–Nd isotopic analyses were made at the Centre for Geodynamics and Geochronology of the Institute of the Earth's Crust SB RAS (Irkutsk, Russia). Details of the analytical procedures are described by Vanin et al. [31]. Isotopic compositions of Nd and concentrations of Sm and Nd were measured on a RPQ Finnigan MAT 262 multi-collector mass spectrometer in static mode. The precision of Sm and Nd contents and $^{147}\text{Sm}/^{144}\text{Nd}$ ratios was ca. 0.5% (2 σ) and ca. 0.005% (2 σ) for $^{143}\text{Nd}/^{144}\text{Nd}$ ratios. All $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were normalised to the standard value of $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$, and adjusted to $^{143}\text{Nd}/^{144}\text{Nd} = 0.521100$ (JNd-1 standard). The mean $^{143}\text{Nd}/^{144}\text{Nd}$ ratio for the JNd-1 standard was 0.512094 ± 0.000002 (2 σ , $n = 20$) during the study. The $\epsilon_{\text{Nd}}(\text{t})$ values and $T_{\text{Nd}}(\text{DM})$ mean crustal residence ages were calculated using currently accepted parameters of CHUR [32]: $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ and $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$ and DM [33]: $^{143}\text{Nd}/^{144}\text{Nd} = 0.513151$ and $^{147}\text{Sm}/^{144}\text{Nd} = 0.2136$.

4. Results

4.1. Geochemistry

The Listvyanka and Goloustnaya dolerites are geochemically similar to subalkaline basalt according to LeBas et al. [34] (Figure 5a). Silica compositions of the studied samples are between 46.7 and 50.4 wt.% and the sum of Na_2O and K_2O varies from 2.2 to 3.9 wt.%. On the Jensen [35] diagram, all dolerites fall in the field of high-Fe tholeiite (Figure 5b).

All the analyzed rocks are characterized by lower to moderate mg#, ranging from 48 to 54 in the Listvyanka dolerites and from 36 to 50 in the Goloustnaya dolerites (Table 1, Figure 6). The dolerites have high contents of TiO_2 (1.6–2.6 wt.% and 2.0–3.3 wt.% in Listvyanka and Goloustnaya dolerites, respectively) and P_2O_5 (0.19–0.31 wt.% and 0.24–0.74 wt.%, respectively) (Table 1, Figure 6). All dolerites demonstrate negative correlations between mg# and TiO_2 , P_2O_5 , La, Th, Zr, and Y (Figure 6).

Primitive mantle-normalized [36] diagrams (Figure 7a) show that the Listvyanka dolerites are characterized by positive Nb-Ta, P and Ti anomalies, a slightly negative Sr anomaly, and variations in the LILE (Rb, Ba, and K). Similar diagrams (Figure 7b) for the Goloustnaya dolerites demonstrate no Nb-Ta and Ti anomalies and negative Sr anomaly. We conclude that the trace element patterns of

Listvyanka and Goloustnaya dolerites are most similar to basalts of the oceanic island basalts (OIB) type (Figure 7a,b).

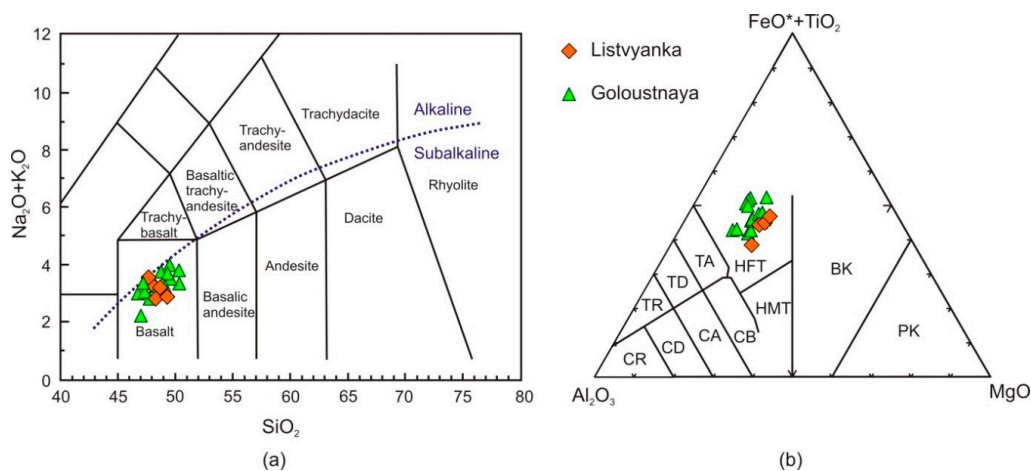


Figure 5. (Na₂O + K₂O)–SiO₂ diagram of LeBas et al. [34] (a); MgO–(FeO* + TiO₂)–Al₂O₃ diagram of Jensen [35] (b) for Listvyanka and Goloustnaya dolerites.

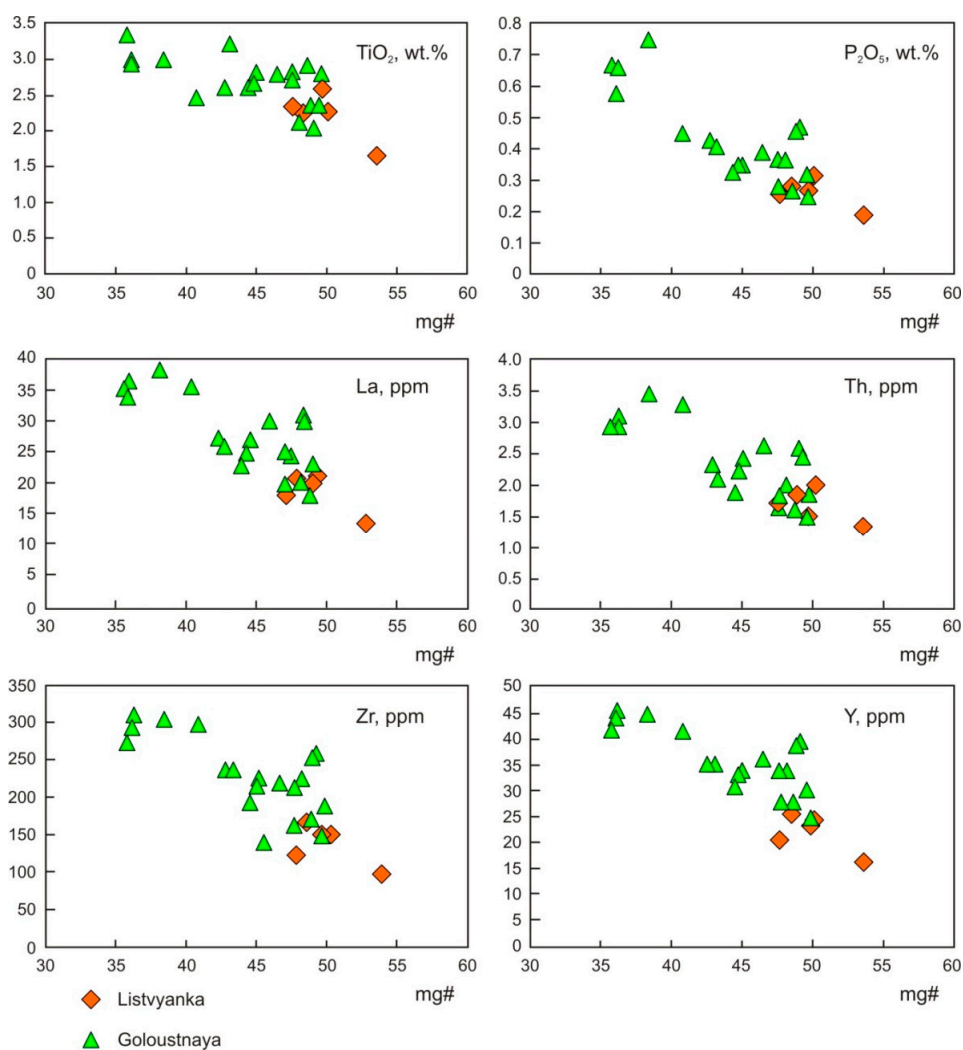


Figure 6. Variation of TiO₂, P₂O₅, La, Th, Zr and Y with magnesium number, mg# for Listvyanka and Goloustnaya dolerites.

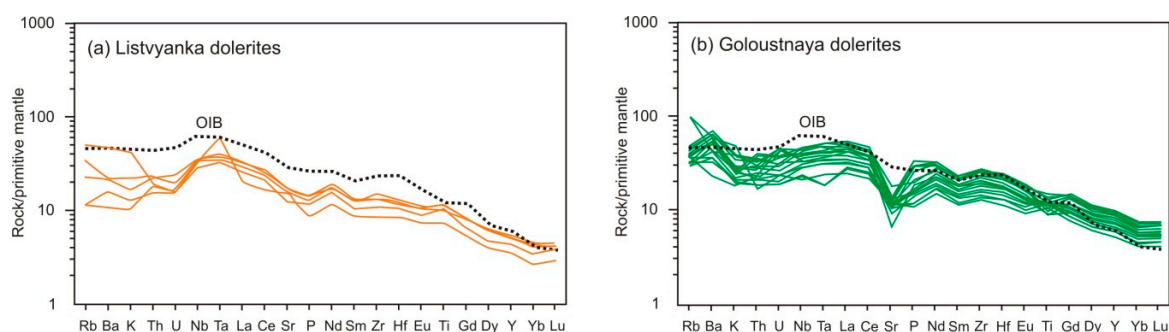


Figure 7. Primitive mantle-normalized [36] multi-element diagrams for Listvyanka (a) and Goloustnaya (b) dolerites. The OIB pattern is after Sun and McDonough [36].

All analyzed samples are enriched in REE. Chondrite-normalized [37] REE patterns of Listvyanka and Goloustnaya dolerites show a similar slight REE fractionation with $(La/Yb)_n = 5.3\text{--}6.7$ and no Eu anomalies ($Eu/Eu^* = 0.92\text{--}1.10$) (Figure 8a,b).

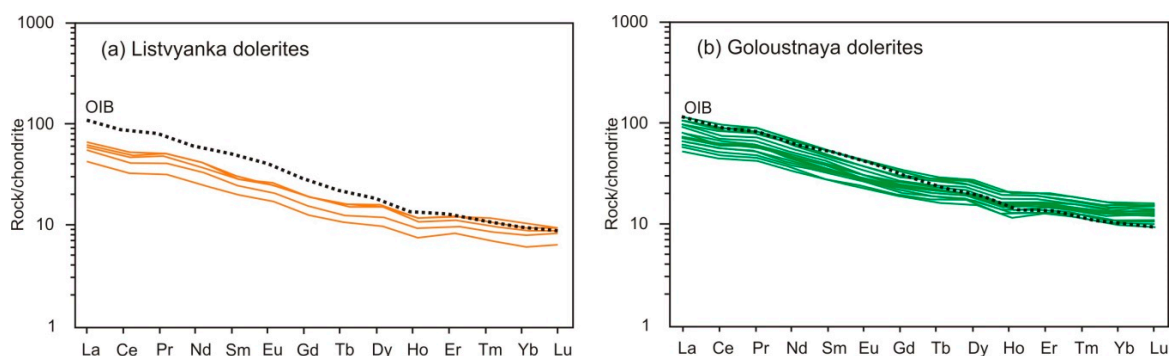


Figure 8. Chondrite-normalized [37] REE patterns for Listvyanka (a) and Goloustnaya (b) dolerites. The oceanic island basalts (OIB) pattern is after Sun and McDonough [36].

4.2. Nd Isotope Systematics

The Sm–Nd isotopic composition was analyzed in three Listvyanka dolerites and five Goloustnaya dolerites (Table 2, Figure 9). The Listvyanka dolerites are characterized by a slightly positive $\epsilon Nd(t)$ values range from +1.1 to +1.5. The $\epsilon Nd(t)$ values for Goloustnaya dolerites are slightly negative and close to zero varying from -0.9 to $+0.1$. The narrow $\epsilon Nd(t)$ range in Listvyanka and Goloustnaya dolerites is apparently consistent with their origin from a relatively homogeneous source. Moreover, $\epsilon Nd(t)$ values in analyzed samples do not correlate with their SiO_2 contents (Figure 9).

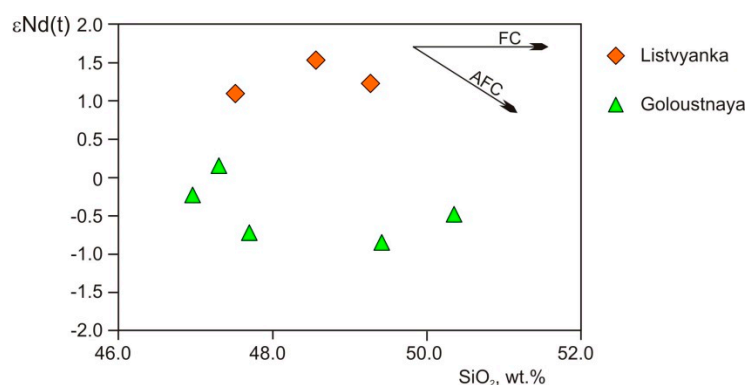


Figure 9. $\epsilon Nd(t)$ – SiO_2 diagram for Listvyanka and Goloustnaya dolerites. FC, fractional crystallization; AFC, assimilation and fractional crystallization.

5. Discussion

5.1. Petrogenesis of Dolerites

The high contents of FeO^* , TiO_2 , P_2O_5 , HFSE (Table 1, Figure 6), primitive mantle-normalized diagrams spidergrams (Figure 7a,b) and chondrite-normalized REE patterns (Figure 8a,b) indicate that the Listvyanka and Goloustnaya dolerites are geochemically close to OIB. All studied dolerites plot near the OIB field in the Zr/Nb – Nb/Th and Nb/Y – Zr/Y diagrams of Condie [38], suggesting that the parent magma originated from a plume-related source (Figure 10a,b).

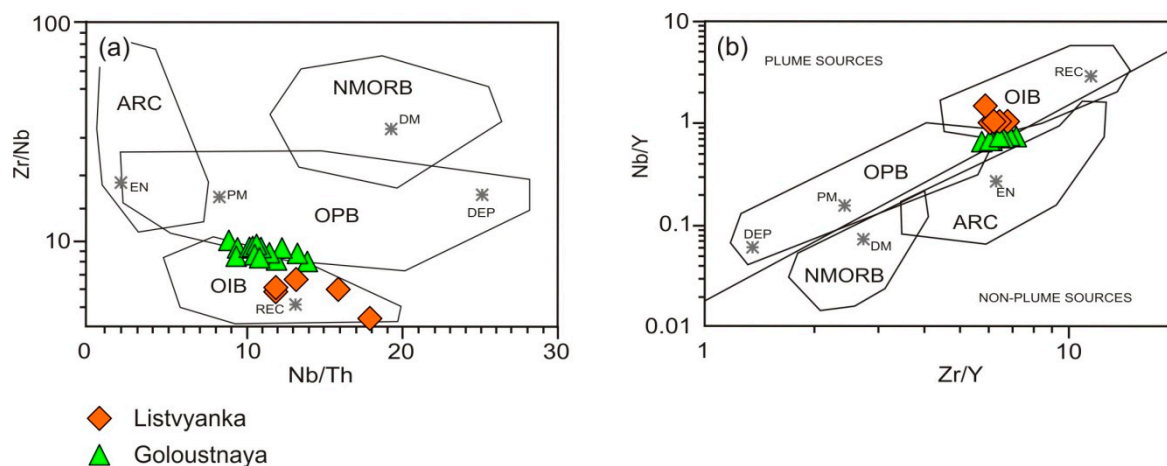


Figure 10. Zr/Nb – Nb/Th (a) and Nb/Y – Zr/Y (b) diagrams [38] for Listvyanka and Goloustnaya dolerites. Abbreviations: ARC, arc-related basalts; NMORB, normal mid-ocean ridge basalts; OIB, oceanic island basalts; OPB, oceanic plateau basalts. DM, shallow depleted mantle; PM, primitive mantle; DEP, deep depleted mantle; REC, recycled component; EN, enriched component.

At the same time, the Listvyanka and Goloustnaya dolerites vary in incompatible element ratios, including Nb/Y , Zr/Nb , Nb/Yb , which reflect the sources and evolution of mafic melts, because they are invariants during fractional differentiation. All studied Listvyanka and Goloustnaya samples plot in the mid-ocean ridge basalts (MORB)–OIB array in the Th/Yb – Nb/Yb diagram of Pearce [39], forming non-overlapping fields (Figure 11a). There are no points above the MORB–OIB array, suggesting the absence of crustal input in mantle sources of all studied dolerites. In the TiO_2/Yb – Nb/Yb diagram of Pearce [39], the Goloustnaya dolerites plot in the tholeiitic OIB field while the Listvyanka dolerites lie near the tholeiitic/alkalic line (Figure 10b). We admit some differences in Listvyanka and Goloustnaya dolerite sources. The geochemical affinities of the Listvyanka dolerites (Figure 7a, Figure 10a,b and Figure 11a,b) as well as their slightly positive $\epsilon\text{Nd}(t)$ values (Figure 9) allow us to assume a mantle plume-related source. As for the Goloustnaya dolerites, their slightly negative $\epsilon\text{Nd}(t)$ value (Figure 9), absence of expressed positive Nb–Ta and Ti anomalies in spidergrams (Figure 7b), and location in the tholeiitic OIB field in the TiO_2/Yb – Nb/Yb diagram (Figure 11b) suggest a possible incorporation of a minor lithospheric component to the mantle plume-related source. Moreover, the increase in Zr/Nb and Nb/Y ratios from Listvyanka to Goloustnaya dolerites (Figure 10) could be related also to an increasing degree of melting in the mantle source.

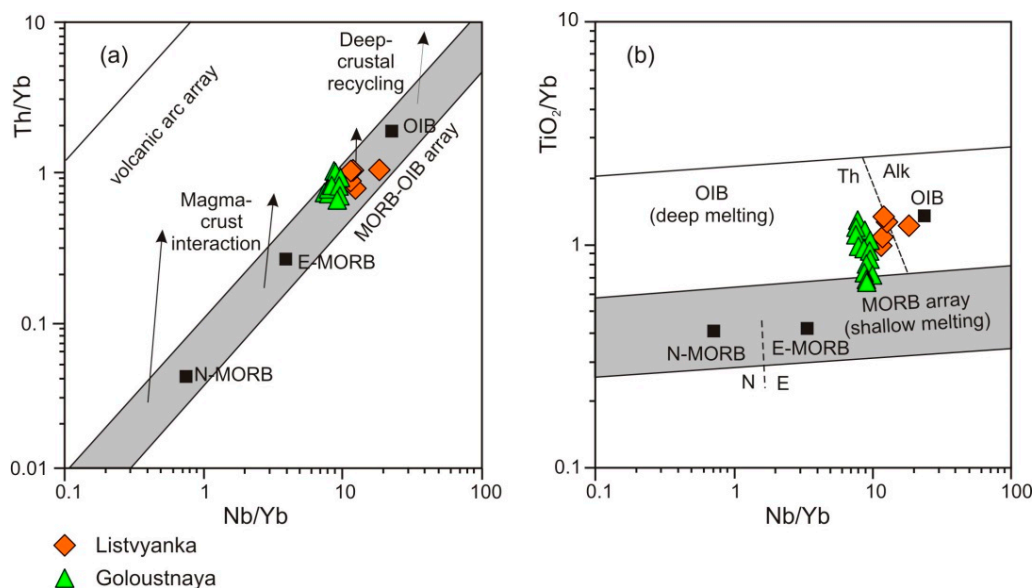


Figure 11. Th/Yb–Nb/Yb (a) and TiO_2/Yb –Nb/Yb (b) diagrams [39] for Listvyanka and Goloustnaya dolerites. Abbreviations: N-MORB, normal mid-ocean ridge basalts; E-MORB, enriched mid-ocean ridge basalts; OIB, oceanic island basalts; Th, tholeiitic OIB; Alk, alkalic OIB.

On the Zr/Y–Zr diagram of Pearce and Norry [40] and Zr/4–Nb*2–Y diagram of Meschede [41], all dolerites fall in the fields of within-plate basalts (WPB) (Figure 12a,b), indicating their formation in an intracontinental extensional setting. We assume that this extension could have been caused by a rising mantle plume. In the Zr/4–Nb*2–Y diagram of Meschede [41] (Figure 12b), both the Listvyanka and Goloustnaya dykes occur in a combined alkali basalt–tholeiite field, but with the Listvyanka dykes plotting closer to the alkaline field (Figure 12b), similar to the pattern in the TiO_2/Yb –Nb/Yb diagram of Pearce [39] (Figure 11b).

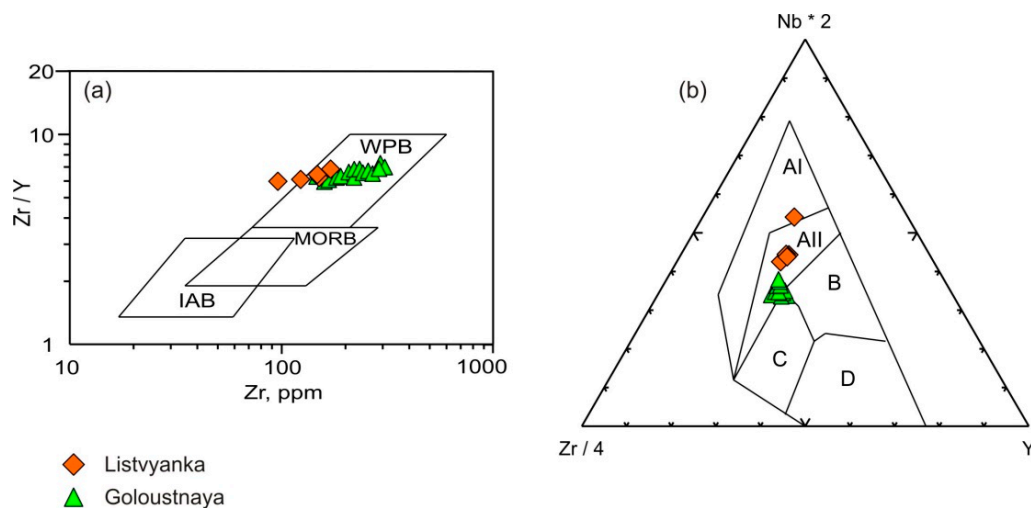


Figure 12. Zr/Y–Zr diagram of Pearce and Norry [40] (a); Zr/4–Nb*2–Y diagram of Meschede [41] (b) for Listvyanka and Goloustnaya dolerites. Abbreviations: (a): IAB, island-arc basalts; MORB, mid-ocean ridge basalts; WPB, within-plate basalts; (b): AI, within-plate alkali basalts; AII, within-plate alkali basalts and within-plate tholeiites; B, E-MORB; C, within-plate tholeiites and volcanic-arc basalts; D, N-MORB and volcanic-arc basalts.

As we mentioned before, the Listvyanka dolerites are a bit older than the Goloustnaya dolerites (1350 ± 6 Ma and 1338 ± 3 Ma, respectively). We assume that some differences in the chemical compositions of the Listvyanka and Goloustnaya dolerites could be related to an increasing extension triggered by a rising mantle plume and some thinning of the lithosphere, which causes some change in melting conditions. These differences may also reflect a possible input of lithospheric component to the mantle plume-related source of the Goloustnaya dolerites.

5.2. Geodynamic Setting

Geochemical and isotopic affinities of the Listvyanka and Goloustnaya dolerites suggest their generation due to a rising mantle plume in the continental lithosphere of the Siberian craton. As mentioned before, the southern part of the Siberian craton was located in close proximity to the northern part of Laurentia in the Mesoproterozoic. These cratons formed the core of Proterozoic supercontinents of Columbia/Nuna and Rodinia [2,5–7], etc. Ernst et al. [7] show that the 1350 ± 6 Ma Listvyanka dolerites of southern Siberia are synchronous with the 1353 ± 2 Ma Barking Dog gabbro sill from the Wellington Inlier of Victoria Island in northern Canada. Moreover, an Sm–Nd imprecise age of 1339 ± 54 Ma was obtained for one dyke in the Sette Daban area of south-eastern Siberia [42]. Thus, two pulses of dolerite magmatism occurred in the southern part of the Siberian craton and in northern Laurentia at ca. 1353 and 1338 Ma. The relatively small age difference (15 million years) between these two pulses suggests that they could be related to the same magmatic event. Geochemical and isotopic data of the Listvyanka and Goloustnaya dolerites suggest that they are related to the same mantle plume, but the more primitive and younger Goloustnaya dolerites could be intruded upon during increasing extension.

The Listvyanka and Goloustnaya dolerites provide the first documented signatures of Mesoproterozoic mafic magmatic activity near the southern margin of the Siberian craton. Slightly older (1381 ± 22 Ma) rift-related anorogenic granitoids were found along the western margin of the Siberian craton (Yenisey Ridge) [43,44]. With uncertainty, this age could also match with the 1385 Ma Chieress LIP of northern Siberia (see below). Older Mesoproterozoic magmatic events related to mantle plumes are widely distributed in the northern part of the Siberian craton (Anabar shield, Olenek uplift, Udzha aulacogen): (i) the dolerite dykes with ages of Sm–Nd 1513 ± 51 Ma [45] and U–Pb 1503 ± 5 Ma [46], as well as the U–Pb 1473 ± 24 Ma intrusions within the Olenek uplift [15] all belonging to the 1501 Ma Kuonmaka LIP [47]; and (ii) the U–Pb 1384 ± 2 Ma dyke [46] in the Anabar shield, U–Pb 1386 ± 30 Ma dykes in the Udzha aulacogen [48], and the Severobyrrang sills of the Taimyr peninsula [49] all belonging to the 1385 Ma Chieress LIP. These events do not have coeval analogues in northern Laurentia [47]. Therefore, there are two separate mantle plumes, which apparently were located directly under the northern part of the Siberian craton at ca. 1501 and 1385 Ma. Coeval magmatic events are recorded not only in the north of the Siberian craton, but also in the Baltica, Congo and San Francisco cratons (see reviews in [18,50–52]). This supports an assumption that Early Mesoproterozoic mafic magmatism might be related to the mantle plume activities within the closely located margins of these ancient cratons in accordance with published paleogeographic reconstructions [19,50,52].

New data show that the focus of early to middle Mesoproterozoic magmatic activity in Siberia migrated from north to south and the ca. 1350 Ma mantle plume was located under the southern part of the Siberian craton and northern Laurentia.

6. Conclusions

1. The 1.35 Ga Listvyanka and 1.34 Ga Goloustnaya dolerite dykes form two Middle Mesoproterozoic swarms in Irkutsk Promontory of the southern part of the Siberian craton. The Listvyanka dykes are sub-vertical with a NNE trend, while the Goloustnaya dykes are characterized by a prevailing W trend.

2. The Listvyanka and Goloustnaya dolerites in their chemical composition correspond to sub-alkaline tholeiitic basalts with lower to moderate mg#, varying from 36 to 54. The trace and rare earth element abundances in these dolerites are generally close to basalts of the OIB type. The Listvyanka dolerites demonstrate slightly positive $\epsilon\text{Nd}(t)$ values (+1.1 to +1.5), while the Goloustnaya dolerites are characterized by lower $\epsilon\text{Nd}(t)$ values varying from -0.9 to $+0.1$.
3. Geochemical and isotopic affinities of the Listvyanka dolerites suggest their enrichment by a mantle plume-related source. Based on geochemical and isotopic data of the Goloustnaya dolerites, we assume some input of a lithospheric component to their mantle plume-related source.
4. The emplacement of the Listvyanka and Goloustnaya dolerites took place in an intracontinental extensional setting, caused by a rising mantle plume.
5. Listvyanka and Goloustnaya dolerites are synchronous with several mafic magmatic events in northern Laurentia and likely represent part of the Mesoproterozoic plumbing system of a Siberian–Laurentian LIP.

Author Contributions: T.V.D. collected samples, interpreted the data, prepared tables and figures, wrote the manuscript; D.P.G. collected samples, helped in the interpretation of data and in writing the manuscript; R.E.E. prepared some figures, helped with the part of the manuscript related to Geodynamic Setting and also reviewed in detail the final version of the manuscript; S.A.P. helped with the preparation of the Introduction and Geodynamic Setting sections; A.M.M. made structural studies and helped with writing the Geological Setting section; E.I.D. performed the Nd isotope study.

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